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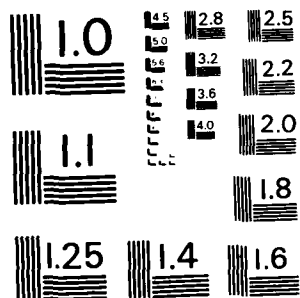CENTER WATERTOWN MA O R GERICKE JUL 83 AMMRC-TR-83-43

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COMPUTER-BASED ULTRASONIC MULTIPLE-FREQUENCY PULSE-ECHO TEST SYSTEM

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OTTO R. GERICKE

MATERIALS INTEGRITY AND TESTING TECHNOLOGY DIVISION

July 1983

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ABSTRACT

A computer-based ultrasonic pulse-echo test system that encompasses three separate ranges of test frequencies is described in this report. Three super-imposed pulse-echo traces are produced, which are displayed in different colors. The system therefore yields amplitude vs time as well as amplitude vs frequency information. Illustrative applications of the test system are discussed, which include determining transducer frequency response, transducer coupling condi-tions, ultrasonic beam diffraction, defect test sensitivity, microstructure of materials, and dispersion.

CONTENTS

INTRODUCTION

The usefulness of ultrasonic waves for the nondestructive evaluation of materials to determine their integrity and uniformity was greatly enhanced by the introduction of the time domain as a test parameter, which led to the pulse-echo test method.[1] Subsequently, to improve the spatial resolution of the method, very short pulses were employed. Since such pulses contain a wide spectrum of frequencies the incorporation of the frequency domain as a test criterion was a logical further development. The evolving technology, which generally is referred to as ultrasonic spectroscopy,[2-5] has produced new insights into ultrasonic evaluation procedures, but has also complicated the thought process required for the interpretation of test results. It is therefore not surprising that the use of the frequency domain in ultrasonic testing is still mostly confined to the laboratory and has not found its way into the quality assurance shop.

The purpose of the development work described here is to simplify the use of the frequency domain by incorporating it directly into pulse-echo testing without sacrificing the time-domain information. The basic concept of the approach is derived from earlier work[6] dealing with the investigation of a dual-frequency ultrasonic pulse-echo method. By taking advantage of today's computer-based colorgraphic display technology it is possible to expand the number of frequency ranges used for the test method to three and, at the same time, provide a clearer display. Using electronic filters, three pulse-echo signals are extracted from a received broadband echo return and are displayed on a computer terminal as red, green, and blue curves. Although these traces are shown superimposed on the display, they can clearly be distinguished by their individual color. For each of the three indications the amplitude vs time relationship is preserved, while the frequency dependence can be derived from a comparison of the amplitude values of the three traces.

In the following, the new test system will be referred to as the Multiple-Frequency Pulse-Echo (MFP) test system to distinguish it from ordinary ultrasonic pulse-echo test equipment.

BASIC INSTRUMENTATION

The components of the test system used for the transmission and reception of broadband pulse-echo signals and for time gating are similar to those used for ultrasonic spectroscopy.[3,5] In contrast to an ultrasonic spectroscope, however, the received echo-signals are not processed by an electronic or computer-based spectrum analyzer. They are instead passed through three individually variable filters to select discrete frequency ranges from the broadband echo return. The analog amplitude vs time functions developed at the outputs of these filters are then digitized and fed into a digital computer equipped with a colorgraphic cathode-ray tube operating system (CRT OS)[7] that produces three superimposed curves

1 FIRESTONE, F. A. *The Supersonic Reflectoscope for Interior Inspection*, Metal Progress, v. 48, 1945, pp. 503-512
2. GERICKE, O. R. *Ultrasonic Spectroscopy of Steel*, Mater. Res. Stds., v. 5, no. 1, January 1965, pp. 23-30.
3 GERICKE, O. R. *Ultrasonic Spectroscopy*, Research Techniques in Nondestructive Testing, R. S. Sharpe, ed., Academic Press, London, 1970, pp. 31-61
4 WHALEY, H. L., and COOK, K. V. *Ultrasonic Frequency Analysis*, Mater. Eval., March 1970, pp. 61-66.
5 BROWN, A. F. *Materials Testing by Ultrasonic Spectroscopy*, Ultrasonics, September 1973, pp. 202-210.
6. GERICKE, O. R. *Dual-Frequency Ultrasonic Pulse-Echo Testing*, J. Acoust. Soc. Am., v. 36, 1964, pp. 313-322.
7 CG Computer System Instruction Manual, CHROMATICS, Inc., Tucker, GA 30084, *Document No. 070002.*

in red, green, and blue color. In areas where the curves overlap the additive colors yellow, magenta, cyan, and white (if all coincide) are obtained. However, to simplify the reproduction of this report, the illustrations used herein do not possess the color features. Instead, red curves will appear as dotted traces, green curves as dashed traces, and blue curves as solid traces.

Center frequency, bandwidth, and output amplitude of the electronic filters used by the system can be individually adjusted for adaptation to the frequency response characteristic of the ultrasonic transducer and/or the ultrasonic transmission properties of the specimen under test.

EQUIPMENT

The major components of the MFP test system are shown by the block diagram of Figure 1 and are the following:

        Transducer
        Pulser/Receiver
        Filter-Digitizer, containing:
            Time Gate
            Filters
            Digitizer
        Oscilloscope
        Computer
        Display
        Disk Drives   .

The transducer contains a highly-damped piezoelectric element and exhibits, therefore, a broad response characteristic covering frequencies of up to 10 MHz. The pulser/receiver provides the initial pulse excitation of the transducer and amplifies the echo signals the transducer subsequently picks up from the test specimen. The receiver bandwidth exceeds that of the transducer.

The amplified signals are fed into specially designed equipment[8] called a Filter-Digitizer, which has several functions. It provides a time gate that is opened after an adjustable delay from the onset of the initial pulse and has a duration variable from 1 to 50 μsec. It extracts three ranges of frequencies from the gated-out signal with the help of filters whose center frequencies are adjustable within the following, overlapping ranges: 0.75 to 2.50 MHz, Filter 1; 1.50 to 5.00 MHz, Filter 2; and 3.00 to 10.00 MHz, Filter 3.

The bandwidth of these filters can, in addition, be individually varied from 0.25 to 1.50 MHz. Their analog amplitude outputs are monitored by an oscilloscope equipped with three input channels and trace intensification to render the position of the time gate visible.

Finally, a digitizer is provided, which sequentially converts the three rectified filter output voltages into digital form and sends the data to the computer via a serial port.

8. *Multiple-Frequency Ultrasonic Pulse-Echo Display System*, Design Automation, Inc., Final Report AD A128338, Contract DAAG46-80-C-0010.
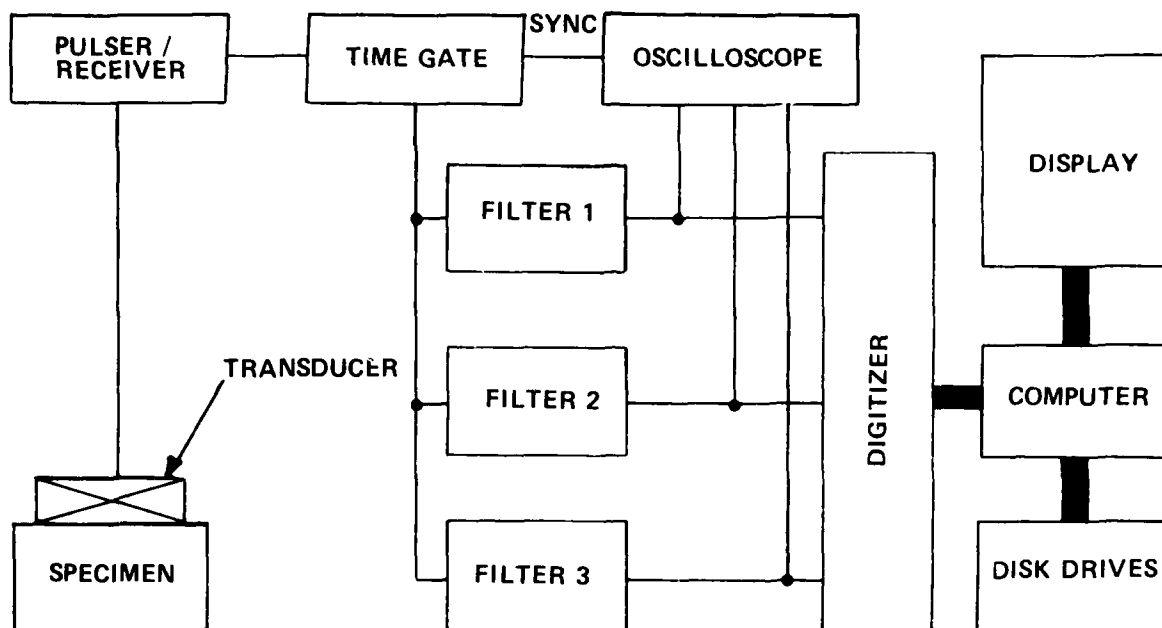
2

Figure 1. Block diagram of Multiple-Frequency Pulse-Echo (MFP) test system.

For the data transfer, a special code is used that produces words consisting of two 8-bit data bytes for each point of the time axis. In addition to the amplitude values, the words contain, in coded form, parameter values representing the settings of the Filter-Digitizer, i.e., the delay between the onset of the initial pulse and the opening of the time gate, the duration of the time gate, the filter number, its center frequency, and bandwidth.

The digitization is carried out over 448 equidistant points on the time axis for each of the three filter outputs in turn with a sampling time of 1 msec per point. The total acquisition time for a set of data is therefore about 1.4 sec.

The data received by the computer is processed with the help of special software and shown as a display produced by a CRT OS, which is part of the computer.[7] Two disk drives are connected to the computer. One is used to store the programs for data processing, the other to record data obtained from test samples for future recall. Up to 40 sets of test data can be stored on a flexible disk inserted into the second disk drive.

SOFTWARE

For processing of test data, special programs are used employing both the BASIC language* capability built into the computer and the much faster object code of the Z-80 microprocessor[9] on which the computer is based. So-called User Functions permit object code subroutines to be incorporated into BASIC language programs.

*BASIC, Version 3.0, Microsoft, Bellevue, WA 98004.
9. LEVENTHAL, L. R. Z-80 Assembly Language Programming, Osborne and Associates, Berkeley, Calif., 1979.

The software package encompasses the following programs:

    KEYS (in CRT OS commands)
    DATAPROC (in BASIC with user functions in Z-80 object code) with
    the following subprograms:
        START
        HIGH-RESOLUTION PLOT
        OVERPLOT
        HIGH-SPEED PLOT
        DATA STORAGE
        DATA RECALL   .

The computer has seven user-programmable function keys, numbered 2 through 8, which have been individually programmed using CRT OS commands (see Appendix A) for the initiation of different phases of the data processing procedure. Combined, these function-key programs have the designation KEYS and are resident on the same magnetic disk that contains program DATAPROC and is inserted into disk drive No. 1. KEYS is transferred to the computer memory by the following Disk Operating System (DOS) command, which is executed after depressing function-key 1:

    FETCH KEYS 4000   .

The execution of this command is the first step after the computer power has been turned on. It is followed by depressing either Keys 2 or 3, both of which load the data-processing program DATAPROC into computer memory, run subprogram START and display a message table explaining the various purposes of the function keys, which are the following:

Key 2 initiates data processing and runs program START (see Appendix B lines 1000 and 1030, respectively), which loads two Z-80 object code programs discussed below into computer memory.

Key 3 has the same function as Key 2 but restricts newly displayed data to the lower half of the CRT screen for the purpose of retaining information previously displayed in the upper half of the CRT.

Key 4 plots coordinates, Filter-Digitizer parameters, and three, superimposed color-coded curves representing the filter output amplitudes. 11 of the 448 values digitized per filter are used for this plot, which takes about 12 sec. Upon its completion, a prompt message is displayed for optional filing of the displayed data, i.e., storage on a flexible disk inserted into disk drive No. 2 that is connected to the computer.

Key 5 permits recall of data, including Filter-Digitizer parameters, that were previously stored on a magnetic disk. The plotting program used in conjunction with this key is the same used with Key 4.

Key 6 plots new amplitude data received from the Filter-Digitizer on top of already displayed curves. Since the display of the parameter values is not altered by this key the settings should not be changed.

Key 7 enlarges the display from half-screen to full-screen size, or, if the RESET button is pressed right after depressing the key, the display shown in the lower half of the CRT is moved to the upper half where it can be retained for reference purposes. After RESET has been pressed, Key 2 or 3 must be used to restart data processing.

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Key 8 produces a repetitive high-speed plot with or without a display of coordinates and Filter-Digitizer parameters. Only every fourth value of the digitized data is used and the total plotting time is thereby reduced to about 3 sec. When this key is actuated, three display options are provided: (a) a repeated display of new data with obliteration of the previous plot, (b) a repeated display of new data superimposed on previous plots, and (c) a repeated display of new data superimposed on previous plots with display of coordinates and the Filter-Digitizer settings according to the latest high-resolution plot.

The HIGH-RESOLUTION PLOT subprogram is in BASIC (see Appendix B, line 2000) and incorporates an object code subroutine shown in assembly language by Appendix C. The corresponding 382 steps of Z-80 object code representing a BASIC user function are contained in the DATA lines 1110 to 1340 of subprogram START (see Appendix B, line 1030). This program uses all 2688 data bytes produced by the Filter-Digitizer, extracts the Filter-Digitizer parameter information to plot coordinates and settings, and produces red, green, and blue curves for the three filter outputs.

Figure 2 illustrates a typical display generated by this program showing the first, second, and third back echo from an aluminum plate obtained with a transducer that has a nominal resonance frequency of 5 MHz. Plotted is the rectified echo amplitude on a linear vertical scale vs time in microseconds. In this figure and most of the figures that will follow, the dotted curve represents a filter frequency of 1.5 MHz, the dashed curve 4 MHz, and the solid curve 10 MHz, with all filter bandwidths equal to 1 MHz. Due to differences in signal delay of 100 to 200 nsec caused by the filtering and rectification process, the maxima of the three signal components do not completely coincide.
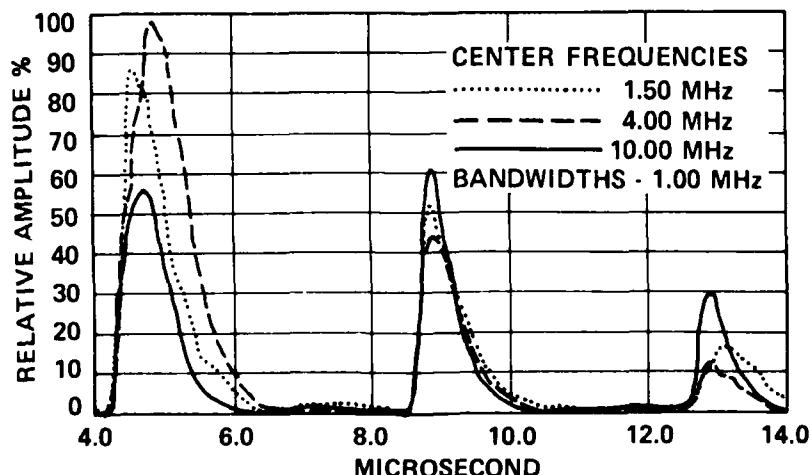
Figure 2. Multiple back-echo train obtained from an aluminum plate with a 5 MHz (nominal) transducer shows three superimposed traces representing the 1.5 (dotted curve), 4 (dashed curve), and 10 MHz (solid curve) signal components.

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Subprogram OVERPLOT (see Appendix B, line 9000) superimposes another set of curves on a high-resolution plot without changing the display of the Filter-Digitizer parameters. The data for these curves is taken from a new digitization process. The program employs the same object code subroutine as subprogram HIGH-RESOLUTION PLOT.

Subprogram HIGH-SPEED PLOT (see Appendix B, line 10000) is in BASIC and incorporates the subroutine shown in assembly language by Appendix D. The associated Z-80 object code is contained in lines 1390 to 1630 of subprogram START (see Appendix B), which loads it into computer memory. In contrast to the object code subroutine used for subprogram HIGH-RESOLUTION PLOT, this subroutine utilizes only every fourth data item available from the digitizer. As a result, plotting of a display takes only 3 sec. The subprogram permits automatic repetitive data acquisition and plotting either with or without erasure of the previously plotted curves. Coordinates and the Filter-Digitizer settings used for the most recent high-resolution plot can be displayed or be omitted. This subprogram is intended primarily for the fast observation of changes in echo signals that occur, for instance, if the transducer is moved along the surface of a specimen that has variations in ultrasonic properties.

The storage of digitized amplitude data and associated Filter-Digitizer parameters on a magnetic disk is done with the help of the DATA STORAGE subprogram that is in BASIC (see Appendix B, line 7000). A prompt message for an optional storage of displayed data appears after each high-resolution plot has been completed.

The recall of data from a flexible magnetic disk is accomplished by the DATA RECALL subprogram that is also in BASIC (see Appendix B, line 5000). This program is called by pressing Key 5 (see above).

APPLICATIONS

In order to demonstrate the practical potential of the MFP test system some illustrative examples of applications shall now be discussed. In view of their fundamental importance, some aspects of ultrasonic transducer performance shall be considered first.

Transducer Frequency Response

An ultrasonic transducer used for pulse-echo testing must be expected to operate over a certain range of frequencies because a pulsed signal is always associated with a spectrum of frequencies. For this reason, the piezoelectric element is usually provided with mechanical damping. Since both the piezoelectric material and the damping body attached to it are difficult to control during manufacture the frequency response characteristics of transducers tend to be rather unpredictable.

Using the MFP test system, transducer response variations can immediately be seen and be compensated for simply by equalizing the output amplitudes of the three filters, while the transducer receives an echo return whose amplitude is not frequency-dependent, such as the back echo from a relatively thin plate of a material that does not exhibit any significant attenuation over the frequency range of interest. Amplitude adjustments necessary for the response equalization can either

be made electronically at the analog filter output or numerically on the digitized data in the computer.

Figure 3 gives an example illustrating the back echo from a 0.25 in. thick aluminum plate before and after the frequency response characteristic of the transducer with a nominal resonance frequency of 5 MHz has been equalized. In this particular case, the filters were tuned to 1.5 (dotted curves), 4 (dashed curves), and 10 MHz (solid curves), with the same bandwidth of 1 MHz. Aluminum was used as material for the test specimen because it exhibits little variation in attenuation over the frequency range involved. To minimize the effects of geometrical attenuation caused by ultrasonic beam diffraction (see below), the specimen was provided with parallel surfaces and a thickness less than the diameter of the transducer, which was 0.5 in. In addition, the specimen surfaces were made very smooth to reduce the layer thickness of the liquid coupling medium and thereby avoid a frequency dependence of the coupling conditions (see below).

These measures assured that as far as the first back echo was concerned the test setup would not introduce a frequency dependence and that the observed response variations would therefore be due predominantly to the characteristics of the transducer itself.

Ultrasonic Beam Diffraction

The cross section of the piezoelectric element contained in an ultrasonic transducer forms an aperture that is one of the factors determining the geometry of the radiated ultrasonic beam. Another is the ultrasonic wavelength that is a function of the ultrasonic velocity in the tested material and the ultrasonic frequency. In a linear system, the wavelength λ, velocity v, and frequency f are connected by the following fundamental relationship:

$$\lambda = v/f \quad . \tag{1}$$

For an ideal piston source, which in a practical situation can only be approximated, the length N of the near field within which the generated ultrasonic beam can be assumed to be parallel is given by[10]

$$N = R^2/\lambda = R^2 \, f/v \quad , \tag{2}$$

where R is the radius of the piston source. Beyond N, the ultrasonic beam is no longer parallel but diverges with an angle γ in accordance with the laws of diffraction

$$\sin \gamma \sim \lambda/2 \, R = v/2Rf \quad . \tag{3}$$

10 KRAUTKRAEMER, J., and KRAUTKRAEMER, H. *Ultrasonic Testing of Materials*, Springer, N.Y., 1969.
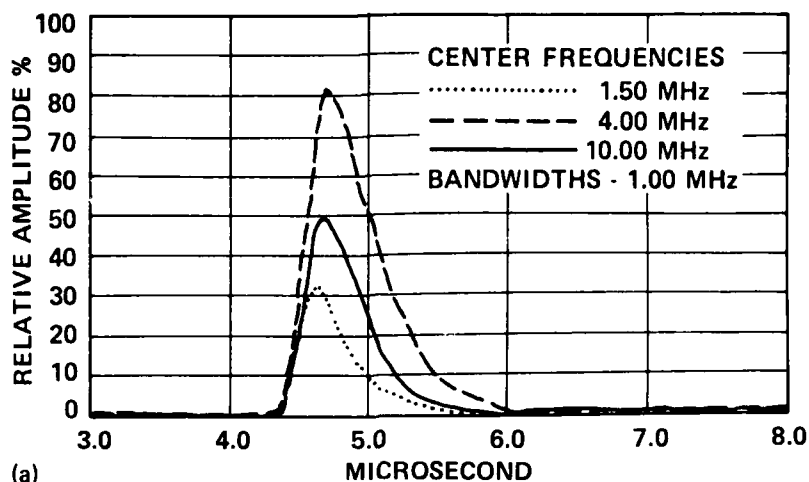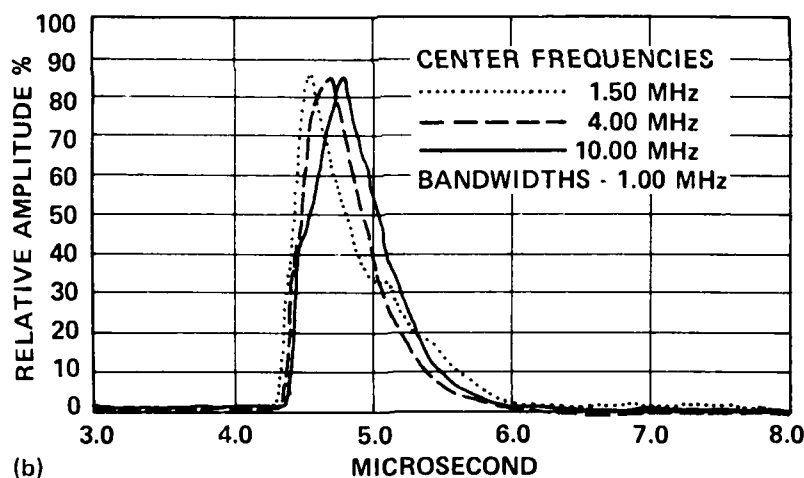
Figure 3. Back echo from an aluminum plate before (a) and after (b) transducer
frequency response equalization (1.5 MHz: dotted curve, 4 MHz: dashed curve,
10 MHz: solid curve).

Beam spreading has the effect that the beam diameter of an echo return will exceed
the transducer diameter, which results in a reduced signal amplitude being received
or so-called geometrical attenuation. If R and v are constants, equation 3 indi-
cates that the geometric attenuation increases with γ, or inversely with the ultra-
sonic frequency f.

   In a practical situation, it is usually not easy to differentiate between
geometrical signal attenuation and other losses caused for instance by the

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microstructure of the tested material or by surface roughness. The fact that transducers are not ideal piston sources and may have a complicated radiation pattern tends to compound this problem.

For an experimental investigation of geometrical losses the MFP test system can be used if specimens are employed that exhibit no other losses. For a frequency range of up to 10 MHz, aluminum blocks with smooth, parallel surfaces that assure good transducer coupling are suitable.

As an example, Figure 4 shows the back echoes from a 2-in. long and a 3-in. diameter aluminum cylinder obtained with equalized transducer response. In comparing the two families of curves, one notes that for the longer block [Figure 4(b)] the solid curve, which represents the highest frequency component of 10 MHz, has the largest amplitude because it suffers the least geometrical attenuation. In the case of the shorter block [Figure 4(a)], the 4 MHz (dashed curve) component exhibits the highest amplitude. This indicates the existence of a more complex diffraction phenomenon than one would expect from equation 3, resulting in a maximum echo return for the 4-MHz frequency range.

The effects of beam spreading can be observed in a different way if a relatively long cylinder is used as a test specimen. In this case, the first longitudinal echo is followed by another echo that is retarded in time because it involves a wave conversion to a slower, transverse mode. The mode conversion is caused by a partial reflection of the beam from the side wall of the specimen and becomes more pronounced as the beam divergence increases, i.e., as the ultrasonic frequency decreases. Figure 5, which illustrates such a satellite echo, shows that its lower frequency components have comparatively larger amplitudes indicating the effect of greater beam divergence.

Transducer Coupling Conditions

If an ultrasonic transducer is placed in direct contact with the test specimen even slight surface irregularities give rise to the formation of an air gap, which constitutes a severe acoustical mismatch. To alleviate this problem, a coupling medium, for instance a thin layer of a liquid, can be introduced between the transducer and the specimen. It is often overlooked that this form of coupling can lead to a frequency-dependence of the ultrasonic energy transfer as can easily be demonstrated with the MFP test system.

To this end, various coupling media were introduced between a 1-in. diameter transducer and a 1-in. thick aluminum plate with smooth, parallel surfaces. Working at room temperature, in each case the first longitudinal back-echo was observed. At the outset, the frequency response of the transducer was equalized using glycerine as a couplant. Figure 6(a) shows the result. The frequencies used are 1.5 (dotted curve), 4 (dashed curve), and 10 MHz (solid curve). Next, water was substituted as a coupling medium which, as Figure 6(b) indicates, produced lower amplitudes for the 1.5- and 10-MHz components but a slightly higher echo signal at 4 MHz (dashed curve). Apparently the greater acoustical mismatch between water and the specimen material that reduces the damping effect on the piezoelectric element produces more favorable results for the frequency range that is close to the element's resonant frequency of 5 MHz.
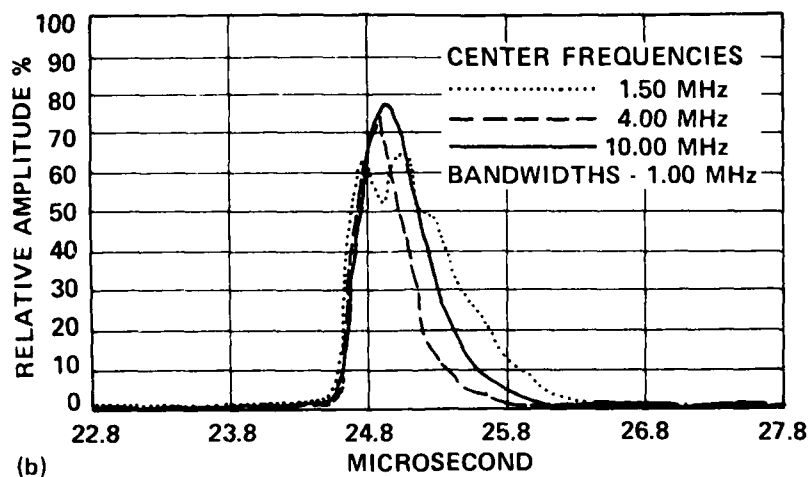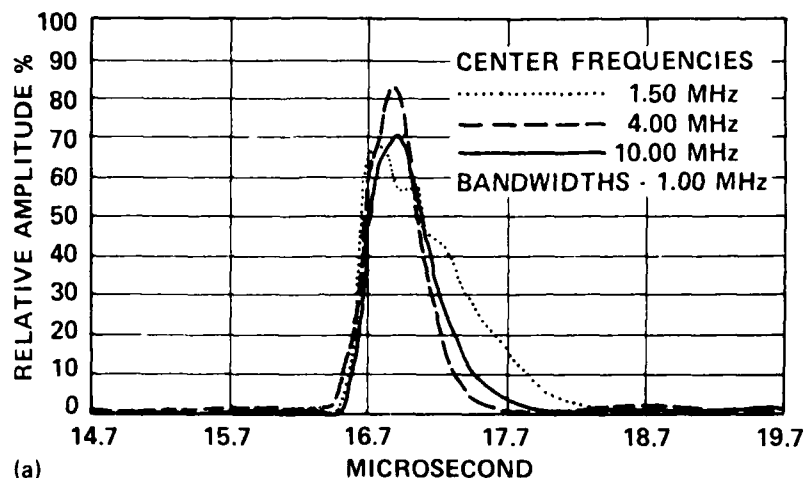
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Figure 4. Back echoes from a 2 in. (a) and a 3 in. (b) long aluminum block illustrate the frequency-dependent effect of beam diffraction on echo amplitude (1.5 MHz: dotted curve, 4 MHz: dashed curve, 10 MHz: solid curve).

As a further example, Figure 7 shows data obtained for two commercial coupling substances.[*] In both cases echo amplitudes for 1.5 and 4 MHz are found to be comparable in magnitude to those obtained with glycerine as a couplant. For the 10 MHz range, however, echoes are smaller.

[*]*AQUASONIC 100*, Parker Laboratories, Inc., Irvingston, NJ 07111, and *SONOTRACE 40*, Echo Laboratories, Lewistown, PA 17044.
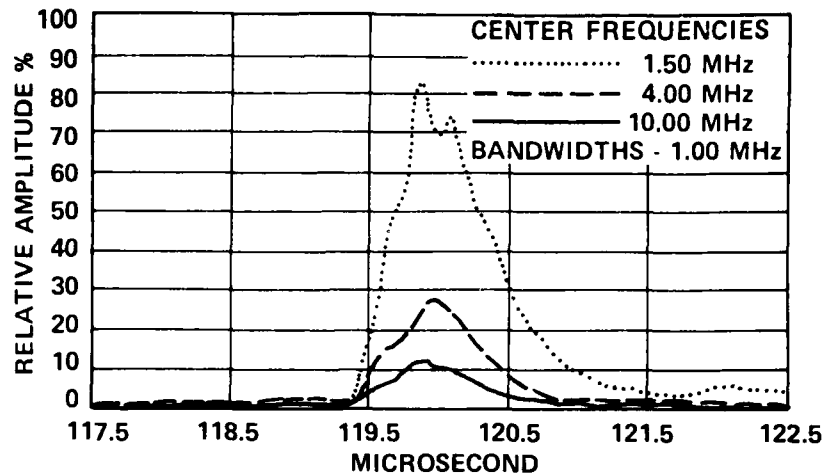
Figure 5. Satellite echo involving transverse mode conversion due to specimen side-wall reflection. The 1.5 MHz (dotted curve) range predominates over the 4 MHz (dashed curve) and 10 MHz (solid curve) components because its larger beam divergence causes side-wall reflections of greater magnitude.

In conducting these experiments, considerable force was used for wringing the transducer down on the specimen surface in order to obtain as thin a layer of couplant as possible. An increase in layer thickness due for example to surface roughness or curvature can be expected to change the frequency-dependence of the coupling conditions.

Complex coupling media can lead to resonance effects. This is illustrated by Figure 8, which was obtained after inserting a thin layer of glycerine followed by a 0.008-in. plastic sheet and another thin layer of glycerine in between transducer and specimen with otherwise unchanged test parameters. One notes significantly reduced echo amplitudes at the lower frequencies, while the 10 MHz echo signal is higher than for all previous coupling conditions. It is obvious from the above examples that for ultrasonic testing involving broadband signals the transducer coupling conditions are of considerable importance.

Test Sensitivity for Isolated Defects

A flat, circular discontinuity located in the far field of a transducer and orientated parallel to the likewise plane test surface returns an echo whose amplitude E is given by[11]

$$E = T \, D/d^2 \, \lambda^2 \quad , \tag{4}$$

where T is the active area of the transducer, D the reflecting area of the discontinuity, d the transducer-to-defect distance, and λ the ultrasonic wavelength. Accordingly, if T, D, and d are considered as fixed parameters, E is inversely
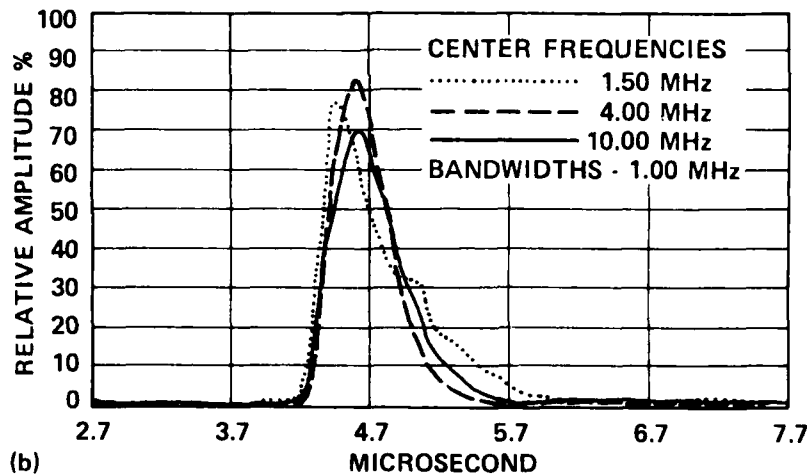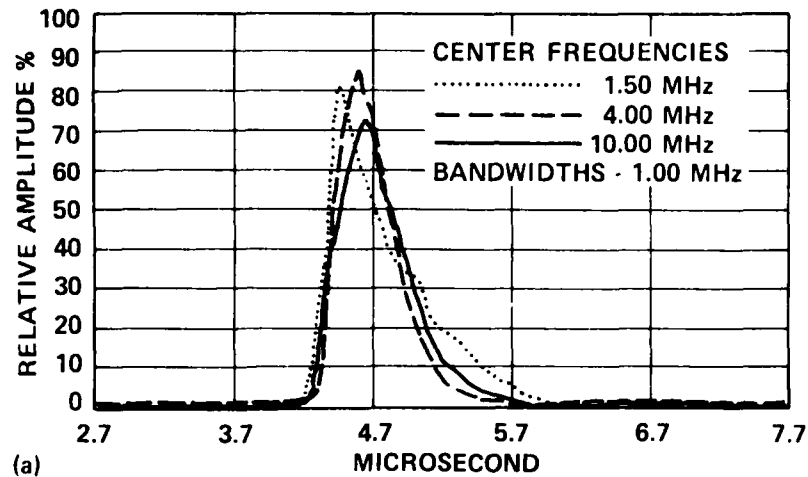
11
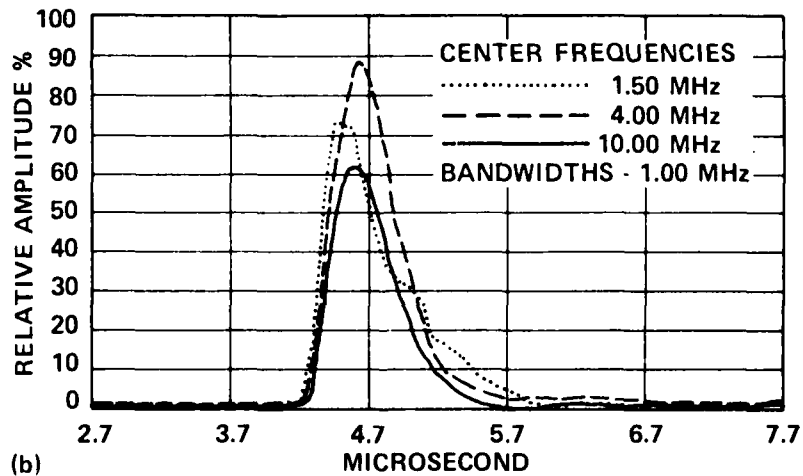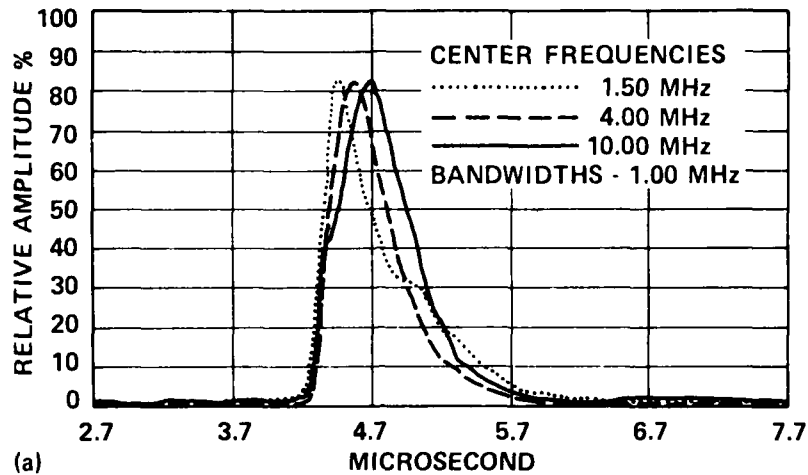
Figure 6. Back echo from aluminum plate using glycerine (a) and water (b) as transducer coupling medium (1.5 MHz: dotted curve, 4 MHz: dashed curve, 10 MHz: solid curve).

proportional to the square of the wavelength, or, assuming a constant ultrasonic velocity, proportional to the square of the ultrasonic test frequency.

This means that the sensitivity for detecting isolated defects improves considerably with increasing ultrasonic test frequency. Unfortunately, the ultrasonic losses of many engineering materials also increase with the frequency. Thus, there normally exists an optimum frequency value for each particular material and specimen geometry. Since the defect size is usually unknown and the attenuation

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Figure 7. Back echo from aluminum plate using AQUASONIC 100 (a) and SONOTRACE 40 (b) as transducer coupling medium (1.5 MHz: dotted curve, 4 MHz: dashed curve, 10 MHz: solid curve).

characteristics of the tested material frequently are uncertain, an experimental determination of the optimum test frequency is desirable and can be accomplished with the MFP system. A practical example is illustrated by Figure 9.

Figure 9(a) shows the echo return from a flat-bottomed hole of 1/8-in. diameter contained in an aluminum block with low ultrasonic losses. In contrast, Figure 9(b) shows an echo from a defect of similar size in a material that has considerable attenuation. One sees, that for aluminum the highest test frequency of 10 MHz

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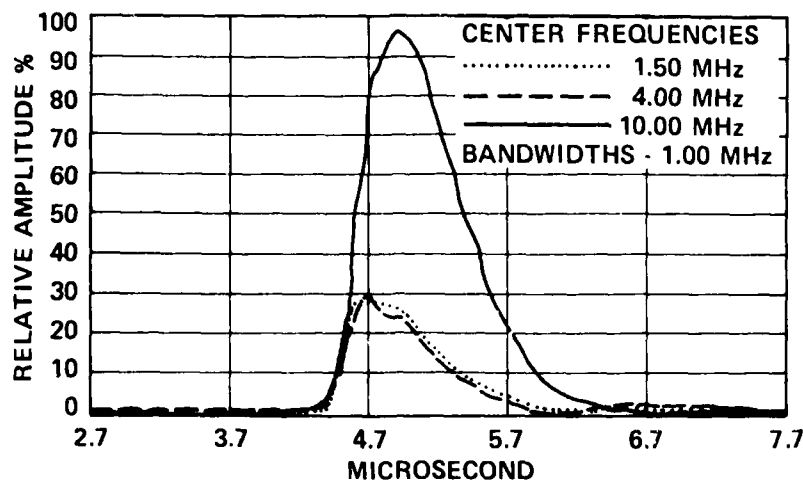
Figure 8. Back echo from aluminum plate using a glycerine-coated plastic sheet as transducer coupling medium that produces an optimum signal amplitude at 10 MHz (solid curve) as compared to 1.5 (dotted curve) and 4 MHz (dashed curve).

(solid curve) produces the largest echo amplitude, while for the plastic material 4 MHz (dashed curve) yields the best test sensitivity. In this case, which involves relatively short transducer-to-defect distances, the results are also influenced by beam diffraction. The MFP test system will take the aggregate effect of these various factors into account.

Microstructure of Materials

The microstructure of materials can often be assessed by determining their ultrasonic attenuation at various test frequencies.[2] The MFP test system can be used for this purpose and will yield relative attenuation values for three selected frequency ranges which may suffice for establishing the general trend of the attenuation vs frequency function. The following figures will show back echoes obtained from specimens made from various materials. The specimens were provided with two plane parallel surfaces to one of which the ultrasonic transducer was coupled. For reference purposes, the transducer response was equalized for the first back echo from a 3-in. long aluminum cylinder whose losses due to scattering at grain boundaries were known to be low. In contrast to aluminum, a polycrystalline structure of copper whose single crystals exhibit pronounced anisotropy gives rise to considerable attenuation caused by scattering of the ultrasonic energy at the acoustically mismatched grain boundaries. Depending on the average grain diameter, losses tend to increase with the ultrasonic test frequency. This is illustrated by Figure 10 obtained for a copper specimen which at 1.5 MHz (dotted curve) still yields a back-echo amplitude equivalent to that of the aluminum reference block but at 4 MHz (dashed curve) and even more so at 10 MHz (solid curve) shows a significant drop in echo amplitude.
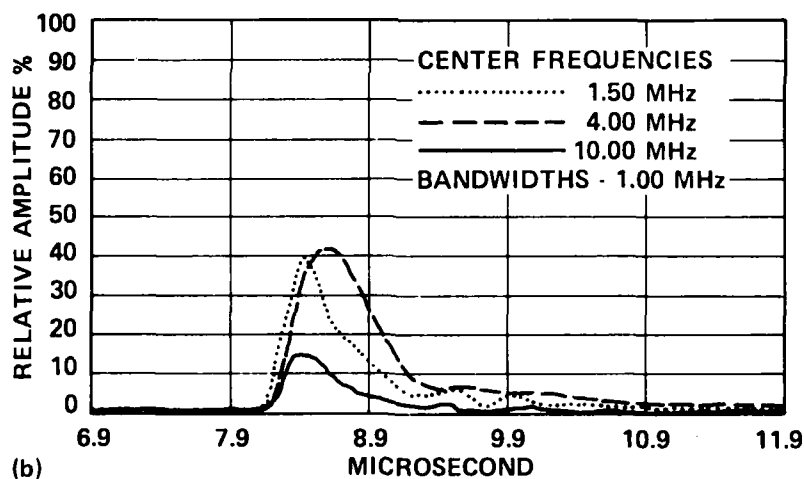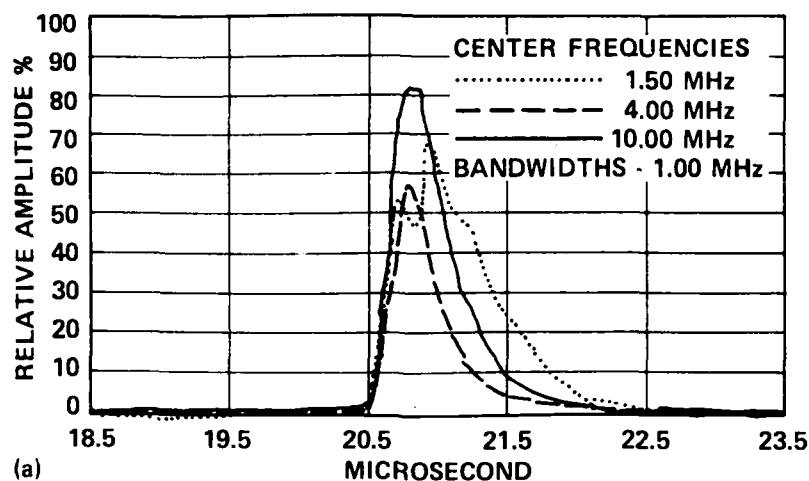
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Figure 9. Back echo from defect in aluminum (a) and plastic (b). Optimum test
frequencies depend on the attenuation characteristics of the materials (1.5 MHz:
dotted curve, 4 MHz: dashed curve, 10 MHz: solid curve).

A material with similar characteristics as copper is titanium for which results
are depicted in Figure 11. For this material, even the 1.5 MHz component (dotted
curve) exhibits a significant reduction in amplitude relative to aluminum. The 10
MHz (solid curve) echo, on the other hand, is larger than observed for copper in
Figure 10.

The next example illustrates how the MFP test system can be used to check on a
sintering process. Figure 12(a) depicts the amplitude equalized data for a specimen
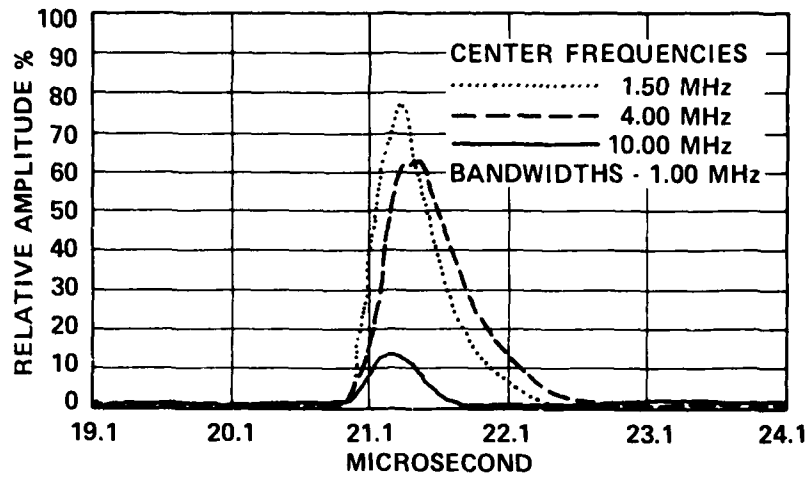
Figure 10. Back echo from copper specimen shows increased signal attenuation at 4 (dashed curve) and 10 MHz (solid curve) as compared to 1.5 MHz (dotted curve).
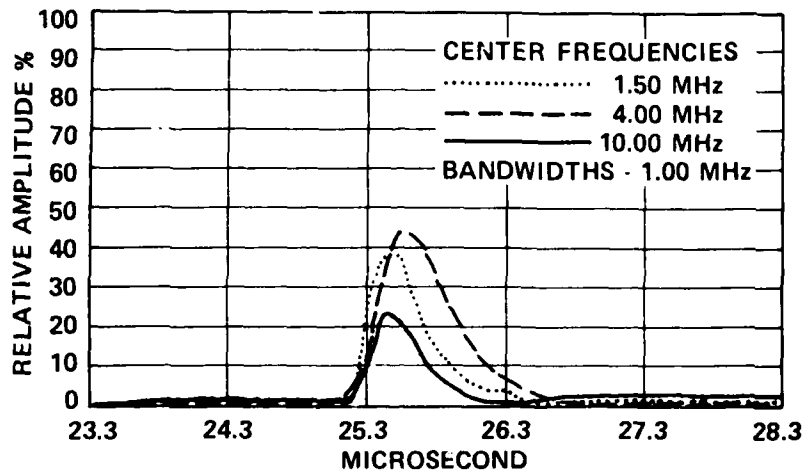
Figure 11. Back echo from titanium specimen shows signal attenuation increasing with frequency (1.5 MHz: dotted curve, 4 MHz: dashed curve, 10 MHz: solid curve).
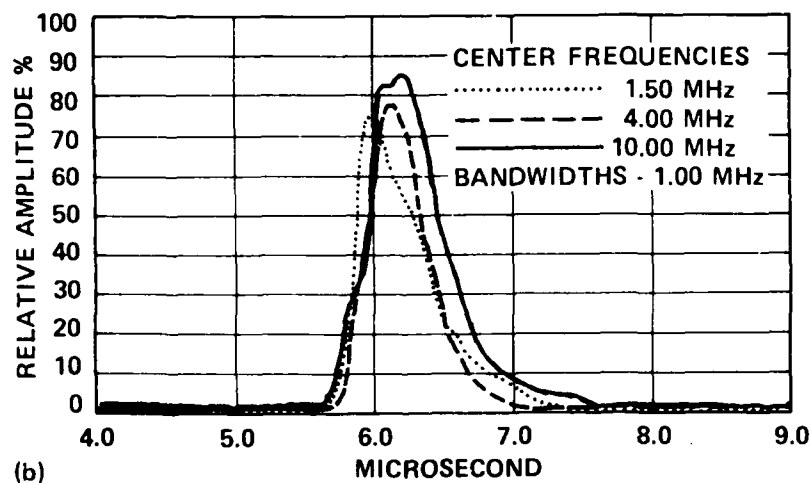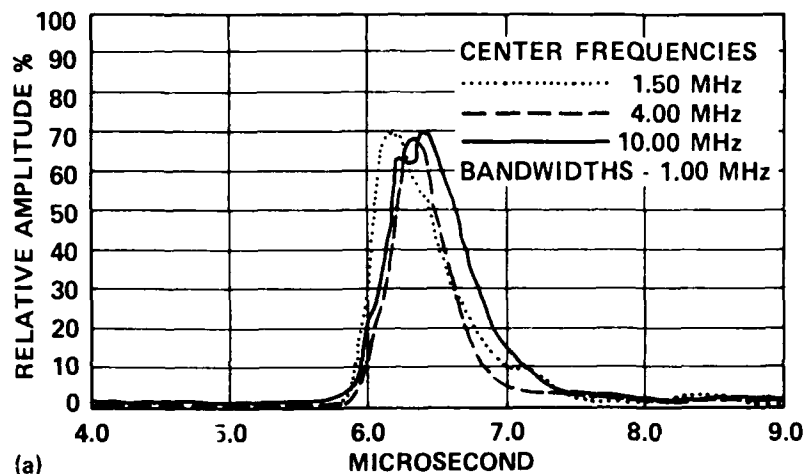
Figure 12. Back echoes from a specimen sintered for 1/2 hour (a) and 4 hours (b)
show differences in pulse attenuation and travel time (1.5 MHz: dotted curve,
4 MHz: dashed curve, 10 MHz: solid curve).

that was sintered for 30 min while Figure 12(b) shows the results obtained for a
longer, 4-hr sintering time. As one sees, the effect of extended sintering on the
ultrasonic properties of the material is twofold. It reduces the ultrasonic pulse
travel time from 5.8 to 5.7 μsec by increasing the ultrasonic velocity in the mate-
rial and it increases the relative amplitude of the 4 MHz and even more so that of
the 10-MHz echo component because of a change in the microstructure. By observing
both these effects together greater reliance on the test can be achieved than by

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checking either the velocity or the attenuation alone in view of the relatively small changes in values that occur.

Dispersion

For materials whose attenuation increases strongly with the ultrasonic test frequency, a dispersion, i.e., a frequency-dependence of the ultrasonic velocity, can be observed. By applying Kramers-Kronig relationship,[11] it has been shown[12] that an increase of ultrasonic attenuation with the frequency leads to a velocity increase with frequency. In simplified form, the velocity change Δv can be expressed by

$$\Delta v \sim \int_{f_1}^{f_2} (\alpha(f)/f^2)\, df \quad , \tag{5}$$

where f_1 and f_2 are the low and the high frequency, respectively, and α is the attenuation function. If a linear increase of the attenuation with the frequency is assumed, that is $\alpha (f) \sim f$, equation 5 can be simplified to

$$\Delta v \sim \int_{f_1}^{f_2} (1/f)\, df \quad . \tag{6}$$

Solving the integral yields

$$\Delta v \sim \ln f_2 - \ln f_1 \quad . \tag{7}$$

To demonstrate the correlation between attenuation and dispersion experimentally, Figure 13 depicts results obtained with the MFP test system for a plastic material that exhibits a strong increase in attenuation with frequency. One notes on this figure that the echo maximum moves to the left and declines in amplitude as the frequency increases from 1 to 3 MHz, which indicates a reduced pulse-travel time or an increase in pulse-propagation velocity being associated with an increase in attenuation in accordance with the theory.

The result of Figure 13 is important from another point of view. It shows that the procedure for determining ultrasonic velocities by measuring the elapsed time from the onset of the initially transmitted pulse to the onset of the back echo yields limited results. If that method had been applied to the discussed example the existence of dispersion would have been overlooked because the first upward departures of the echo traces from the time axis coincide for all frequency components.

11. KRONIG, R., and KRAMERS, H. A. *Absorption and Dispersion in X-Ray Spectra*, Z. Phys., v. 48, 1928, p. 174.
12. O'DONNELL, M., JAYNES, E. T., and MILLER, J. G. *Kramers-Kronig Relationship Between Ultrasonic Attenuation and Phase Velocity*, J. Acoust. Soc. Am., v. 69, 1981, p. 696.
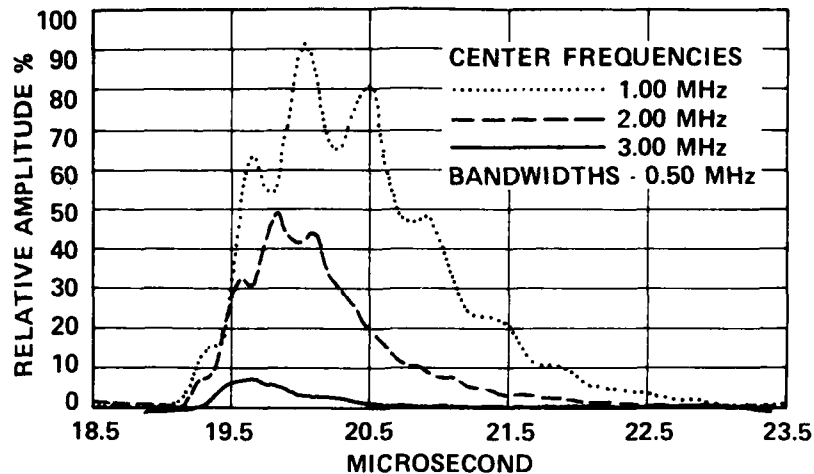
Figure 13. Back echo from a plastic plate shows strong increase of signal attenuation with frequency (1.5 MHz: dotted curve, 4 MHz: dashed curve, 10 MHz: solid curve) accompanied by decrease in pulse travel time due to dispersion.

CONCLUSIONS

The discussed applications of the Multiple-Frequency Pulse-Echo, or MFP test highlight its practical potential and indicate its main advantage: to permit the simultaneous observation of time- as well as frequency-dependent ultrasonic test phenomena.

In addition, the computer-generated CRT presentation of the system provides two display windows and thus permits a comparison of test data. For instance, new test results can be compared with previously obtained reference data. The use of reference information is facilitated by the magnetic data storage capability incorporated in the system.

ACKNOWLEDGMENTS

APPENDIX A.   FUNCTION KEY PROGRAMS

```
KEY F 2
(ESC)B43000
DOS"LOAD/1 DATAPROC"
RUN 1000


KEY F 3
(ESC)OA0(MODE)W0,2555110,(ESC)B43F00
DOS"LOAD/1 DATAPROC"
RUN 1670


KEY F 4
(ESC)OA0(MODE)W0,2555110,(ESC)OA0(MODE)C6F2/F3 FIRST
RUN 2000


KEY F 5
(ESC)OA0(MODE)W0,2555110,(ESC)OA0(MODE)C6F2/F3 FIRST
RUN 5000


KEY F 6
(ESC)OA0(MODE)W0,2555110,(ESC)OA0
RUN 9000


KEY F 7
(MODE)W0,5115110,(MODE)Z0,2555110,


KEY F 8
(ESC)OA0(MODE)W0,2555110,(ESC)OA0
RUN 10000
```

APPENDIX B.   DATA PROCESSING PROGRAMS

```
1000 'PROGRAM DATAPROC 12MAY82
1010 '=========================
1020 '
1030 'SUBPROGRAM START
1031 '----------------
1032 '
1040 PRINT CHR$(12);"~K";"~Y5,~X3,~C7~1WAIT~2";
1050 POKE 49021!,1
1060 DIM AR$(387)
1070 FOR N=0 TO 381
1080 READ AR$(N)
1090 POKE 17104+N,VAL("&H"+AR$(N))
1100 NEXT
1110 DATA D9,21,E8,B4,1,6,E,1E,32,DB,4D,CB,4F,C2,EA,42
1120 DATA 1D,3E,0,BB,C2,D9,42,C3,17,43,DB,4C,CB,7F,C2,0
1130 DATA 43,B,C3,D7,42,1E,32,DB,4D,CB,4F,CA,10,43,DB,4C
1140 DATA 77,23,B,3E,0,B8,C2,F5,42,B9,C2,F5,42,C3,1B,43
1150 DATA 1D,3E,0,BB,C2,F7,42,32,CC,42,C9,21,30,B5,11,CE
1160 DATA BF,1,49,0,ED,A8,3E,0,B9,C2,24,43,FD,21,E8,B4
1170 DATA 1E,3,DD,21,F8,A7,DD,36,0,1,DD,23,DD,36,0,47
1180 DATA DD,23,DD,36,0,1,DD,23,DD,36,0,42,DD,23,C3,F8
1190 DATA 43,21,3F,0,1,BE,1,23,54,CB,22,CB,22,7D,CB,3F
1200 DATA CB,3F,CB,3F,CB,3F,CB,3F,CB,3F,82,E6,7,C6,40,DD
1210 DATA 23,DD,77,0,DD,2B,7D,E6,3F,C6,40,DD,77,0,DD,23
1220 DATA DD,23,FD,7E,0,CB,27,CB,27,CB,27,CB,27,57,FD,23
1230 DATA FD,7E,0,CB,3F,CB,3F,CB,3F,82,CB,3F,FE,64,FA,A6
1240 DATA 43,3E,C7,C3,A8,43,CB,27,FD,23,C6,37,57,E6,3F,C6
1250 DATA 40,DD,77,0,DD,23,7A,E6,C0,CB,3F,CB,3F,CB,3F,CB
1260 DATA 3F,CB,3F,CB,3F,C6,40,DD,77,0,DD,23,B,3E,0,B8
1270 DATA C2,57,43,B9,C2,57,43,1D,BB,C2,4E,43,DD,36,0,1
1280 DATA DD,23,DD,36,0,3A,DD,23,DD,36,0,46,DD,23,DD,36
1290 DATA 0,1E,DD,23,D9,36,1,C9,FD,23,FD,23,FD,23,FD,23
1300 DATA DD,36,0,28,DD,23,DD,36,0,1,DD,23,DD,36,0,43
1310 DATA DD,23,FD,7E,0,E6,30,CB,3F,CB,3F,CB,3F,CB,3F,FE
1320 DATA 0,CA,2E,44,FE,1,CA,33,44,3E,31,C3,35,44,3E,34
1330 DATA C3,35,44,3E,32,DD,77,0,DD,23,DD,36,0,1,DD,23
1340 DATA DD,36,0,3A,DD,23,DD,77,0,DD,23,C3,51,43
1350 FOR N=0 TO 387
1360 READ AR$(N)
1370 POKE 17500+N,VAL("&H"+AR$(N))
1380 NEXT
1390 DATA D9,21,E8,B4,1,1,E,1E,32,DB,4D,CB,4F,C2,76,44
1400 DATA 1D,3E,0,BB,C2,65,44,C3,A3,44,DB,4C,CB,7F,C2,8C
1410 DATA 44,B,C3,63,44,1E,32,DB,4D,CB,4F,CA,9C,44,DB,4C
1420 DATA 77,23,B,3E,0,B8,C2,81,44,B9,C2,81,44,C3,A7,44
1430 DATA 1D,3E,0,BB,C2,83,44,32,CC,42,C9,FD,21,E8,B4,1E
1440 DATA 3,DD,21,F8,A7,DD,36,0,1,DD,23,DD,36,0,47,DD
1450 DATA 23,DD,36,0,1,DD,23,DD,36,0,42,DD,23,C3,82,45
1460 DATA 21,3F,0,1,6F,0,23,23,23,23,54,CB,22,CB,22,7D
1470 DATA CB,3F,CB,3F,CB,3F,CB,3F,CB,3F,CB,3F,82,E6,7,C6
1480 DATA 40,DD,23,DD,77,0,DD,2B,7D,E6,3F,C6,40,DD,77,0
1490 DATA DD,23,DD,23,FD,7E,0,CB,27,CB,27,CB,27,CB,27,57
1500 DATA FD,23,FD,7E,0,CB,3F,CB,3F,CB,3F,82,CB,3F,FE,64
1510 DATA FA,24,45,3E,C7,C3,26,45,CB,27,FD,23,FD,23,FD,23
1520 DATA FD,23,FD,23,FD,23,FD,23,C6,37,57,E6,3F,C6,40,DD
```

```
1530 DATA 77,0,DD,23,7A,E6,C0,CB,3F,CB,3F,CB,3F,CB,3F,CB
1540 DATA 3F,CB,3F,C6,40,DD,77,0,DD,23,B,3E,0,B8,C2,D2
1550 DATA 44,B9,C2,D2,44,1D,BB,C2,C9,44,DD,36,0,1,DD,23
1560 DATA DD,36,0,3A,DD,23,DD,36,0,46,DD,23,DD,36,0,1E
1570 DATA DD,23,D9,36,1,C9,FD,23,FD,23,FD,23,FD,23,FD,23
1580 DATA FD,23,FD,23,FD,23,DD,36,0,28,DD,23,DD,36,0,1
1590 DATA DD,23,DD,36,0,43,DD,23,FD,7E,0,E6,30,CB,3F,CB
1600 DATA 3F,CB,3F,CB,3F,FE,0,CA,C0,45,FE,1,CA,C5,45,3E
1610 DATA 31,C3,C7,45,3E,34,C3,C7,45,3E,32,DD,77,0,DD,23
1620 DATA DD,36,0,1,DD,23,DD,36,0,3A,DD,23,DD,77,0,DD
1630 DATA 23,C3,CC,44
1640 PRINT CHR$(27);"OA0";"¯W0,511511255¯K¯P";
1650 PRINT CHR$(27);"OA0";
1660 GOTO 1680
1670 PRINT CHR$(27);"OA0";"¯W0,2555110,";CHR$(12);
1680 PRINT"¯X2,¯Y3,¯C4¯M¯C7¯N¯C4          FUNCTION KEYS          ¯M¯C0¯N"
1690 PRINT"¯X1,¯Y2,¯C2F2: STARTS DATA PROCESSING"
1700 PRINT"¯C3F3: RE-STARTS DP AFTER ¯M¯C4¯N¯C7 RESET ";
1701 PRINT"¯M¯C0¯N¯C7 TO WORK IN LOWER HALF OF SCREEN"
1710 PRINT"¯C6F4: PLOTS DIGITIZER DATA WITH HIGH RESOLUTION"
1720 PRINT"¯C3F5: PLOTS DATA STORED ON DISK IN DRIVE 2 WITH";
1721 PRINT" HIGH RESOLUTION"
1730 PRINT"¯C7F6: PLOTS NEW DATA OVER PREVIOUS HIGH RESOLUTION PLOT"
1740 PRINT"    (CAN BE REPEATED)"
1750 PRINT"¯X1,¯Y2,¯C6F7: EXPANDS PLOT TO FULL SCREEN SIZE
1760 PRINT"¯C2F7 & ¯M¯C4¯N¯C7 RESET ¯M¯C0¯N¯C2: MOVES DISPLAY";
1761 PRINT" TO UPPER HALF OF SCREEN"
1770 PRINT"¯C7F8: STARTS REPEATED ¯C6HIGH SPEED ¯C7PLOTTING";
1780 PRINT" WITH OPTIONAL "
1790 PRINT"    CURVE SUPERPOSITION, ¯M¯C7¯N¯C0 BREAK";
1791 PRINT" ¯M¯C0¯N¯C7 WILL STOP THE PLOTTING"
1800 END
1801 '
2000 'SUBPROGRAM HIGH-RESOLUTION PLOT
2001 '-----------------------------
2002 '
2005 PRINT CHR$(12);"¯C2¯K¯X3,¯Y6,¯1WAIT¯X1,¯Y1,¯2";
2010 PRINT CHR$(27);"R0F"
2020 DEFUSR0=17104
2030 POKE 17100,255
2040 AA=USR0(ZZ)
2050 IF PEEK(17100)=255 THEN GOTO 2110
2060 PRINT "¯N¯C4";"FILTER-DIGITIZER IS NOT RESPONDING ";
2070 PRINT "PROPERLY."   :PRINT
2080 PRINT "CORRECT PROBLEM AND PRESS KEY ";"¯C5";"F4";
2090 PRINT "¯C4";" AGAIN."
2100 END
2110 POKE 49019!,4
2120 'PROGRAM XF 09FEB82
2130 CLEAR 1000
2140 ON ERROR #0 GOTO 0
2150 DEFINT C,I-N,R-S,X
2160 DIM SD(4),S(35),V$(0)
2170 F1=0:F2=0:F3=0:B1=0
2180 B2=0:B3=3:DEL=-1:IVL=0:SC=0
```

```
2190 PRINT CHR$(27);"OA1";"~W065056511255~N~C1~K~P";
2200 PRINT CHR$(27);"OA2";"~W417244502254~M~C4~N~C3~K~P";
2210 PRINT CHR$(27);"OA3";"~W070032511042~M~C6~J~P~N~C4";
2220 PRINT CHR$(27);"OA0";"~W0,2555110,~K~P~N~C7";CHR$(21);
2230 PRINT CHR$(27);"OA0";"~~K~P~N~C7";CHR$(21);CHR$(12);
2240 LF=PEEK(49019!)
2250 IF LF=4 THEN GOTO 2300
2260 IF LF<>5 THEN 2290
2270 GOSUB 4230
2280 GOTO 2310
2290 PRINT CHR$(12);"~C4~Y3,";"ERROR: ENTRY CODE = ";LF;"~C7":END
2300 POKE 49020!,0
2310 PRINT CHR$(12);"~~C3~X3,~Y6,~1WAIT~X1,~Y1,~2";
2320 GOSUB 3600
2330 IF PEEK(49020!)=1 THEN SC=PEEK(49027!)
2340 GOSUB 2540
2350 IF PEEK(49020!)=1 THEN GOSUB 4200
2360 IF LF<>5 THEN 2410
2370 PRINT CHR$(27);"W";
2380 PRINT"~";F";CHR$(27);"OA2";CHR$(12);CHR$(31);CHR$(31);
2390 PRINT"#";F1$;CHR$(27);"OA0";
2400 PRINT CHR$(28);:END
2410 GOSUB 3790
2420 PRINT CHR$(21);CHR$(27);"OA3";CHR$(12);
2430 PRINT"~C4TO FILE DATA: ~C5FILE & RETURN~C4, ELSE:";
2431 PRINT" ~C5RETURN ~C4ONLY~C5";
2440 O$=""
2450 INPUT O$
2460 PRINT "~M~C0";CHR$(12);"~~M~C6~K";
2470 PRINT CHR$(27);"OA3";CHR$(21);"~~U236042~M~C0~N~C3MICROSECONDS"
2480 IF O$="FILE" THEN GOSUB 3860
2490 IF O$="FILE" THEN 2510
2500 PRINT CHR$(27);"OA0";CHR$(11);CHR$(28);:END
2510 GOSUB 7000
2520 PRINT"~=";CHR$(11);CHR$(11);CHR$(11);CHR$(11);CHR$(11);
2530 PRINT:PRINT"~C2~Y6,~X3,    FILING DONE        ":END
2540 PRINT CHR$(12);"~~K";
2550 PRINT "~X1,~Y1,~G'~P~C3";:PLOT 64,55,64,255:
2560 PLOT 64,55,511,55
2570 PRINT CHR$(21);
2580 PRINT "~C3~V~U004199";"RELATIVE";"~U024205";"AMPLITUDE"
2590 IF SC>0 THEN PRINT CHR$(12);"~H~C4~1~Y6,~X3,USE LIN":END
2600 PRINT "~H~U004109";"(%)"
2610 GOSUB 2910
2620 PRINT "~U000030";"DISPLAY";
2630 PRINT "~U000020";"BEGINS AT";
2640 PRINT "~U000010";"MICROSECONDS";
2650 PRINT "~U236042";"MICROSECONDS";
2660 PRINT CHR$(14);"~U061053";"#";"~U061044";"*"
2670 PRINT"~U061036";"8";"~U074020";"-III,";CHR$(15);
2680 GOSUB 3020
2690 PRINT "~U000020";"BEGINS AT ";
2700 IF INT(DEL)>-1 AND INT(DEL)<10 THEN PRINT USING "#.# ";DEL;
2710 IF INT(DEL)>9 AND INT(DEL)<100 THEN PRINT USING "##.#";DEL;
2720 IF INT(DEL)>99 THEN PRINT USING "###.#";DEL;
```

```
2730 PRINT"~C4";
2740 PRINT "~U152020";"F= ";
2750 IF F1>0 THEN PRINT USING "##.## MHZ";F1
2760 PRINT "~U144010";"BW= ";
2770 IF B1>0 THEN PRINT USING "##.## MHZ";B1
2780 PRINT "~C2";
2790 PRINT "~U280020";"F= ";
2800 IF F2>0 THEN PRINT USING "##.## MHZ";F2
2810 PRINT "~U272010";"BW= ";
2820 IF B2>0 THEN PRINT USING "##.## MHZ";B2
2830 PRINT "~C1";
2840 PRINT "~U416020";"F= ";
2850 IF F3>0 THEN PRINT USING "##.## MHZ";F3
2860 PRINT "~U408010";"BW= ";
2870 IF B3>0 THEN PRINT USING "##.## MHZ";B3
2880 ON (IVL+1) GOSUB 3220,3290,3360,3420,3480,3540
2890 IF LF=5 THEN GOSUB 4200
2900 RETURN
2910 PRINT "~U031255";"100";"~U041215";"80"
2920 PRINT "~U041175";"60";"~U041135";"40"
2930 PRINT "~U041095";"20";"~U051059";"0"
2940 RETURN
2950 PRINT"~V~M~C0~X004~Y002~U032255";
2960 FOR N=0 TO 9
2970 PRINT CHR$(32);
2980 NEXT
2990 PRINT "~U028059";CHR$(32);
3000 PRINT "~H~N~C7~X001~Y001";
3010 RETURN
3020 PRINT CHR$(27);"0A1";CHR$(12);
3030 PRINT "~G'~C3";:PLOT 64,55,64,255: PRINT "~C3";
3040 FOR N=0 TO 396 STEP 44
3050 PLOT 108+N,255,108+N,56
3060 NEXT
3070 ON SC+1 GOTO 3080,3080,3080,3160,3120
3080 FOR N=0 TO 180 STEP 20
3090 PLOT 65,75+N,511,75+N
3100 NEXT
3110 GOTO 3190
3120 FOR N=0 TO 175 STEP 25
3130 PLOT 65,80+N,511,80+N
3140 NEXT
3150 GOTO 3190
3160 FOR N=0 TO 167 STEP 33
3170 PLOT 65,88+N,511,88+N
3180 NEXT
3190 PRINT"~C3";:PLOT 65,255,511,255:PLOT 504,255,504,56
3200 PRINT CHR$(27);"0A0";
3210 RETURN
3220 FOR N=0 TO 4
3230 IF N<4 THEN K=88*N ELSE K=348
3240 PRINT "~C3~U";:PLOT 140+K,54:
3250 PRINT USING "#.#";(N+1)/5
3260 NEXT
3270 VL=1
```

```
3280 RETURN
3290 FOR N=0 TO 4
3300 IF N<4 THEN K=88*N ELSE K=348
3310 PRINT "~C3~U";:PLOT 140+K,54:
3320 PRINT USING "#.#";.4+.4*N
3330 NEXT
3340 VL=2
3350 RETURN
3360 FOR N=0 TO 4
3370 PRINT "~C3~U";:PLOT 140+N*68,54:
3380 PRINT N+1
3390 NEXT
3400 VL=5
3410 RETURN
3420 FOR N=0 TO 4
3430 PRINT "~C3~U";:PLOT 140+88*N,54:
3440 PRINT USING "##";2*N+2
3450 NEXT
3460 VL=10
3470 RETURN
3480 FOR N=0 TO 4
3490 PRINT "~C3~U"; :PLOT 140+88*N,54:
3500 PRINT USING "##"; 4*N+4
3510 NEXT
3520 VL=20
3530 RETURN
3540 FOR N=0 TO 4
3550 PRINT "~C3~U";:PLOT 132+88*N,54:
3560 PRINT 10*N+10
3570 NEXT
3580 VL=50
3590 RETURN
3600 FOR N=0 TO 34
3610 NA=PEEK(49030!+2*N)
3620 S(N+1)=1-INT(64 AND NA)/64
3630 NEXT
3640 'DEL CALC
3650 DEL=0
3660 FOR N=0 TO 3
3670 SD(N)=8*S(4*N+1)+4*S(4*N+2)+2*S(4*N+3)+S(4*N+4)
3680 DEL=DEL+(10^(2-N))*SD(N)
3690 NEXT
3700 IF S(35)=1 THEN SC=3 ELSE SC=0
3710 IVL=4*S(17)+2*S(18)+S(19)
3720 F1=(4*S(20)+2*S(21)+S(22))*.25+.75
3730 F2=(4*S(23)+2*S(24)+S(25))*.5+1.5
3740 F3=4*S(26)+2*S(27)+S(28)+3
3750 B1=(((2*S(29)+S(30))*2) MAX 1)/4
3760 B2=(((2*S(31)+S(32))*2) MAX 1)/4
3770 B3=(((2*S(33)+S(34))*2) MAX 1)/4
3780 RETURN
3790 PRINT CHR$(27);"OA0";"~K~P~N~C7";CHR$(21);
3800 POKE 17100,1
3810 DEF USR0=17104:X=USR0(0)
3820 IF PEEK(17100)=0 THEN PRINT"~C4~Y2,DIGITIZER OUT":END
```

```
3830 PRINT CHR$(27);"W"; 'PLOTTING
3840 PRINT"~:F";CHR$(28)
3850 RETURN
3860 PRINT CHR$(27);"OA3";CHR$(12);"~M~C6~N~C5ASSIGN FiLE # ";
3870 W$=""
3880 INPUT "(8 CHARACTERS):";F$
3890 FOR N=1 TO LEN(F$)
3900 H$=MID$(F$,N,1)
3910 IF H$<"0" OR H$>"Z" OR H$>"9" AND H$<"A" THEN 3930
3920 W$=W$+H$
3930 NEXT
3940 L=LEN(W$)-7
3950 IF L>0 THEN GOTO 4000
3960 FOR N=0 TO -L
3970 W$="0"+W$
3980 L=L+1
3990 NEXT
4000 F1$=MID$(W$,L,4)+"-"+RIGHT$(W$,4)
4010 F2$=RIGHT$(W$,8)
4020 PRINT CHR$(12);F1$;
4030 Z$=""
4040 INPUT "       OK FOR NEW FILE? - YES OR NO";Z$
4050 IF Z$="YES" THEN GOTO 4150
4060 IF Z$<>"NO" THEN GOTO 4020
4070 Z$="" :PRINT CHR$(12)
4080 PRINT "REASSIGN #? - TYPE ";"~N~C5";"FILE";"~N~C4";
4090 PRINT ", OR IF DONE? -PRESS ";"~C5";"CR";"~C4";".";
4100 INPUT Z$
4110 IF Z$="FILE" GOTO 3860
4120 IF Z$<>"" GOTO 4070
4130 NF=0
4140 RETURN
4150 PRINT CHR$(27);"OA2";CHR$(12);CHR$(31);CHR$(31);"#";F1$;
4160 POKE 49020!,1  'FILE FLAG
4170 NF=1   '"NEW FILE" FLAG
4180 PRINT "~C0~K"; CHR$(28)
4190 RETURN
4200 PRINT CHR$(27);"OA2";CHR$(12);CHR$(31);CHR$(31);"#";F1$;
4210 PRINT CHR$(27);"OA0";
4220 RETURN
4230 F1=PEEK(49013!)/4
4240 F2=PEEK(49014!)/4
4250 F3=PEEK(49015!)/4
4260 B1=PEEK(49016!)/4
4270 B2=PEEK(49017!)/4
4280 B3=PEEK(49018!)/4
4290 DD=100*PEEK(49023!)+10*PEEK(49024!)+PEEK(49025!)
4300 DEL=DD+.1*PEEK(49026!)
4310 IVL=PEEK(49022!)
4320 F2$=""
4330 FOR N=1 TO 8
4340 U=PEEK(48999!+N)
4350 IF U<48 OR U>90 OR U>57 AND U<65 THEN GOTO 4400
4360 F2$=F2$+CHR$(PEEK(48999!+N))
4370 NEXT
```

```
4380 F1$=LEFT$(F2$,4)+"-"+RIGHT$(F2$,4)
4390 RETURN
4400 F1$=" (NONE) "
4410 RETURN
4411 '
5000 'SUBPROGRAM DATA RECALL
5001 '---------------------
5002 '
5010 CLEAR 2000
5020 DIM A$(50),B$(50),C$(10)
5030 ON ERROR #0 GOTO 0
5040 PRINT CHR$(27);"OA1";"~W152195344085~R";
5050 PRINT CHR$(27);"OA0";"~W0,2555110,";
5060 PRINT CHR$(27);"OA0";
5070 PRINT CHR$(12);"~C7";"TO RETRIEVE A RECORD FROM DISKFILE:"
5080 PRINT :PRINT SPC(10);"FIRST  - LOAD THE APPROPRIATE DISK ";
5090 PRINT "IN DRIVE #2." :PRINT
5100 K=0   :Y=0
5110 ON ERROR GOTO 5140
5120 DOS"LDDIR /2 A$"
5130 GOTO 5150
5140 RESUME
5150 PRINT "~N~C2~U200215";"DIRECTORY"
5160 B$(0)="***********************"
5170 B$(2)=B$(0)
5180 B$(1)=A$(0)
5190 FOR N=3 TO 50
5200 IF LEFT$(A$(N-2),1)="" THEN GOTO 5230
5210 B$(N)=A$(N-2)
5220 GOTO 5260
5230 F=N-3 MAX 8
5240 Y=(N-3) MIN 3
5250 GOTO 5270
5260 NEXT
5270 IF F=0 THEN GOTO 5310
5280 PRINT "~C4~U";
5290 PLOT 125,(174-10*Y)
5300 PRINT CHR$(14);"++%";CHR$(15);"~C2~K";
5310 GOSUB 5560
5320 PRINT CHR$(27);"OA0";"~U080070~C7";"SECOND - SCROLL THE ";
5330 PRINT "DIRECTORY UP OR DOWN UNTIL THE";"~U152060";
5340 PRINT "RED ARROW POINTS TO THE DESIRED FILE#.";"~U152050";
5350 PRINT "USE THE GRAY CURSOR CONTROLS, ";"~C5";CHR$(14);"'";
5360 PRINT "~C7";CHR$(15);" AND ";"~C5";CHR$(14);"&";
5370 PRINT "~C7";CHR$(15);".";
5380 PRINT "~U080030";"THIRD  - WHEN READY, ";
5390 PRINT "PRESS ";"~C5";"L";"~C7";" TO LOAD THE FILE, - OR"
5400 PRINT "~U152020";"SELECT ANOTHER DISK AND PRESS ";"~C5";"R";
5410 PRINT "~C7";" FOR REPEAT, -";"~U152010";
5420 PRINT "OR PRESS ";"~C5";"CR";"~C7";" TO EXIT THE PROGRAM.";
5430 ON ERROR #1 GOTO 5450
5440 GOTO 5440
5450 IF ERR=24 THEN Q=INP(&H4A) ELSE ON ERROR #0 GOTO 0
5460 IF Q=76 OR Q=82 OR Q=13 THEN RESUME 5500
5470 IF Q=11 THEN GOSUB 5640
```

```
5480 IF Q=10 THEN GOSUB 5730
5490 RESUME
5500 IF Q=82 GOTO 5030
5510 IF Q=13 GOTO 6210
5520 IF Q=76 GOTO 5910
5530 PRINT CHR$(12);"~C4";"ERROR - START AGAIN!   PRESS ";
5540 PRINT "KEY ";"~C5";"F5";"~C4";"."
5550 END
5560 '
5570 PRINT CHR$(27);"OA1";"~K";CHR$(21);
5580 FOR N=0 TO 10
5590 IF N=0 OR N=2 THEN PRINT"~N~C6";ELSE PRINT"~N~C2";
5600 IF N<10 THEN PRINT B$(N) ELSE PRINT B$(N);
5610 ON ERROR GOTO 0
5620 NEXT
5630 RETURN
5640 'UP ONE LINE SUBROUTINE
5650 PRINT CHR$(27);"OA1";
5660 PRINT "~U152095";CHR$(10);
5670 IF K+12>0 THEN L=(K+11)MOD(F+3)
5680 IF K+12<=0 THEN L=F+2-ABS(K+12)MOD(F+3)
5690 IF L=0 OR L=2 THEN PRINT "~C6"; ELSE PRINT "~C2";
5700 PRINT B$(L);
5710 K=K+1
5720 RETURN
5730 '
5740 PRINT CHR$(27);"OA1";
5750 PRINT "~U152195"; CHR$(11);
5760 IF K>0 THEN L=(K-1)MOD(F+3) ELSE L=F+2-ABS(K)MOD(F+3)
5770 IF L=0 OR L=2 THEN PRINT "~C6"; ELSE PRINT "~C2";
5780 PRINT B$(L);
5790 K=K-1
5800 RETURN
5810 '
5820 PRINT CHR$(27);"OA0";"~P";
5830 ON ERROR #0 GOTO 0
5840 PRINT "~U380165~C4";"SELECT ";"~C2";".ABS ";"~C4"
5850 PRINT "~U380145";"FILES ONLY!"
5860 FOR N=1 TO 400 :PRINT CHR$(7) :NEXT
5870 PRINT "~?020";
5880 PRINT "~U380165~C0";"             ";"~C7";
5890 PRINT "~U380145";"            "
5900 RETURN
5910 'LOAD SEQUENCE
5920 PRINT CHR$(27);"OA0";"~X003~Y006~1~C6~U000165";"WAIT~2"
5930 M=(F+2) MAX 8
5940 R=K+Y+2
5950 IF R=>0 THEN L=R MOD (M+1) ELSE L=M-(ABS(R+1) MOD (M+1))
5960 P$=LEFT$(B$(L),8)
5970 Q$=MID$(B$(L),10,3)
5980 IF Q$="ABS" GOTO 6010
5990 GOSUB 5810
6000 GOTO 5430
6010 '
6020 OT=PEEK(49021!)
```

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```
6030 DOS"FETCH "+PS+"/2 "+HEX$(43000!)+" "
6040 PRINT "~X001~Y001"
6050 POKE 49019!,5
6060 POKE 49021!,OT
6070 ERASE A$,B$,C$
6080 CLEAR
6090 ON ERROR #0 GOTO 0
6100 GOTO 2130 'TO HIGH-RESOLUTION PLOT
6110 RESUME 6120
6120 '
6130 NF=0  :E$=""   :PRINT "~R"
6140 IF ERR=70 GOTO 6200
6150 IF ERR=71 GOTO 6210
6160 IF ERR=82 GOTO 6220
6170 IF ERR=83 GOTO 6230
6180 IF ERR=119 GOTO 6240
6190 GOTO 6250
6200 E$="#14."   :GOTO 6270
6210 E$="#15."   :GOTO 6270
6220 E$="#20."   :GOTO 6270
6230 E$="#21."   :GOTO 6270
6240 E$="#45."   :GOTO 6270
6250 E$="AS NOTED BELOW."
6260 EF=1
6270 PRINT CHR$(12);"~C4";
6280 F1$=LEFT$(PS,4)+"-"+RIGHT$(PS,4)
6290      "DISK SYSTEM HAS REJECTED REQUEST ";
6300 PRINT "TO LOAD #";F1$;","
6310 PRINT "CLAIMING DOS ERROR ";E$   :PRINT
6320 PRINT "~C6";"CORRECT PROBLEM AND TYPE ";"~C5";"GO";
6330 PRINT"~C6";". TO EXIT PROGRAM, PRESS ";"~C5";"CR";"~C6";"."
6340 IF EF=1 THEN ON ERROR #0 GOTO 0
6350 K$=""
6360 INPUT K$
6370 IF K$="" THEN GOTO 6210
6380 IF K$="GO" THEN GOTO 5030
6390 PRINT
6400 GOTO 6320
6401 '
7000 'SUBPROGRAM DATA STORAGE
7001 '----------------------
7002 '
7010 GOSUB 7050
7020 GOSUB 7280
7030 IF NF=1 THEN GOSUB 7470
7040 RETURN
7050 POKE 49013!,4*F1
7060 POKE 49014!,4*F2
7070 POKE 49015!,4*F3
7080 POKE 49016!,4*B1
7090 POKE 49017!,4*B2
7100 POKE 49018!,4*B3
7110 POKE 49019!,6
7120 POKE 49022!,IVL
7130 L1=INT(DEL/100)
```

```
7140 L2=INT((DEL-100*L1)/10)
7150 L3=INT(DEL-100*L1-10*L2)
7160 L4=INT((DEL-100*L1-10*L2-L3)*10)
7170 POKE 49023!,L1
7180 POKE 49024!,L2
7190 POKE 49025!,L3
7200 POKE 49026!,L4
7210 POKE 49027!,SC
7220 IF F2$="" THEN F2$=" (NONE) "
7230 FOR N=1 TO 8
7240 Q$=MID$(F2$,N,1)
7250 POKE 48999!+N,ASC(Q$)
7260 NEXT
7270 RETURN
7280 PRINT CHR$(27);"OA0";"~W0,2555110,";
7290 PRINT CHR$(27);"OA0";CHR$(21);CHR$(12);CHR$(28);"~C7"
7300 PRINT"FILE # ";
7310 FOR N=1 TO 8
7320 IF N=5 AND F2$<>" (NONE) " THEN PRINT "-";
7330 PRINT CHR$(PEEK(48999!+N));
7340 NEXT
7350 PRINT"~C7  F1=";PEEK(49013!)/4;
7360 PRINT "   F2=";PEEK(49014!)/4;
7370 DD=100*PEEK(49023!)+10*PEEK(49024!)+PEEK(49025!)
7380 DEL=DD+.1*PEEK(49026!)
7390 PRINT "   F3=";PEEK(49015!)/4;"  DELAY=";DEL
7400 PRINT "B1=";PEEK(49016!)/4;
7410 PRINT "   B2=";PEEK(49017!)/4;
7420 IVL=PEEK(49022!)
7430 IF IVL<3 THEN VL=IVL^2+1 ELSE VL=10*((IVL-3)^2+1)
7440 PRINT "   B3=";PEEK(49018!)/4,"INTERVAL=";VL
7450 RETURN
7460 '
7470 '
7480 GOSUB 7960
7490 IF AF=-1 THEN PRINT ELSE GOTO 7520
7500 PRINT "~C4";"CHECK DRIVE 2 FOR PROBLEM!"
7510 GOTO 7550
7520 PRINT "DISK DRIVE #2 AVAILABLE FILE SPACES:";AF;"."
7530 IF AF>0 GOTO 7620 ELSE PRINT
7540 PRINT "~C4";"CHANGE DISK IN DRIVE 2; NO SPACE REMAINS."
7550 PRINT "TO RESUME, TYPE ";"~C5";"GO";"~C4";" WHEN READY.";
7560 PRINT "  TO CANCEL FILING, PRESS ";"~C5";"CR";"~C4";"."
7570 INPUT Z$
7580 IF Z$<>"GO" THEN NF=0   :GOTO 7950
7590 GOSUB 7280
7600 GOTO 7470
7610 GOTO 7950
7620 PRINT "~=~C6":PRINT"~X2,~Y4,~1WAIT, ~2FILING IN PROGRESS"
7630 ON ERROR GOTO 7690
7640 DOS"STORE "+F2$+"/2 "+HEX$(43000!)+" "+HEX$(49102!)+" "
7650 DOS"COMPRESS/2"
7660 DOS"FETCH "+F2$+"/2 "+HEX$(43000!)+" "
7670 EF=0   :NF=1
7680 GOTO 7950
```

```
7690 '
7700 NF=0   :E$=""    :PRINT ""R"
7710 IF ERR=70 GOTO 7770
7720 IF ERR=71 GOTO 7780
7730 IF ERR=82 GOTO 7790
7740 IF ERR=83 GOTO 7800
7750 IF ERR=119 GOTO 7810
7760 GOTO 7820
7770 E$="#14."   :GOTO 7840
7780 E$="#15."   :GOTO 7840
7790 E$="#20."   :GOTO 7840
7800 E$="#21."   :GOTO 7840
7810 E$="#45."   :GOTO 7840
7820 E$="AS NOTED BELOW."
7830 EF=1
7840 PRINT ""C4" :PRINT "DISK SYSTEM HAS REJECTED REQUEST ";
7850 PRINT "TO FILE #";F1$;","
7860 PRINT "CLAIMING DOS ERROR ";E$   :PRINT
7870 IF EF=1 GOTO 7680
7880 PRINT ""C6";"CORRECT PROBLEM AND TYPE ";""C5";"GO";
7890 PRINT""C6";".  TO OMIT FILING, PRESS ";""C5";"CR";""C6";"."
7900 K$=""
7910 INPUT K$
7920 IF K$="" THEN GOTO 7950
7930 IF K$="GO" THEN RESUME 7470
7940 PRINT  :GOTO 7880
7950 RETURN
7960 '
7970 ON ERROR GOTO 8020
7980 DOS"LDDIR /2 V$"
7990 AS=VAL("&H"+RIGHT$(V$(0),4))
8000 AF=INT(AS/43)
8010 GOTO 8040
8020 AF=-1
8030 RESUME 8040
8040 RETURN
8041 '
9000 'SUBPROGRAM OVERPLOT
9001 '-------------------
9002 '
9010 PRINT CHR$(27);"R9F";:DEF USR0=17104
9020 PRINT CHR$(21);CHR$(28):PRINT""C2"1NEW DATA"2"K"
9030 POKE 17100,255
9040 X=USR0(0)
9050 IF PEEK(17100)=255 THEN GOTO 9080
9060 PRINT CHR$(28):PRINT""N"C4DIGITIZER INOPERATIVE"
9070 END
9080 PRINT CHR$(11);""C6"1PLOTTING"2"
9090 PRINT CHR$(27);"W";
9100 PRINT"":F";
9110 PRINT CHR$(21);CHR$(28):PRINT"            ":END
9111 '
10000 'SUBPROGRAM HIGH-SPEED PLOT
10001 '--------------------------
10002 '
```

```
10010 PRINT CHR$(27);"GA0";CHR$(12);CHR$(27);"R0F";"~K~P";
10011 DEF USR1=17500:GG=0
10020 DIM S(35)
10030 PRINT"~Y3,~C6FOR SUPERIMPOSED CURVES ENTER: ~C2~X3,1~X1,"
10040 PRINT"FOR CURVES WITH COORDINATES ENTER:";
10041 PRINT" ~C4~X3,2~X1,~C7 (MUST FOLLOW ~C2F4~C7)"
10050 PRINT"~C6FOR REPEATED NEW PLOTS: ~M~C7~N~C0 RETURN ~M~C0~N~C6 ONLY"
10060 INPUT GG:PRINT CHR$(12);
10070 IF GG=1 THEN NN=0:GOTO 10120
10080 IF GG=2 THEN 10160
10090 PRINT CHR$(21);CHR$(28);"~C7~X3,~Y4,~1*~2";:X=USR1(0)
10100 PRINT CHR$(12);CHR$(27);"W";
10110 GOTO 10090
10120 X=USR1(0)
10130 PRINT CHR$(27);"W";
10140 NN=NN+1:PRINT "~C7";CHR$(28);CHR$(21);NN
10150 GOTO 10120
10160 POKE 49020!,0:GOSUB 4230:GOSUB 3600:SC=0:GOSUB 2540
10170 X=USR1(0)
10180 PRINT CHR$(27);"W";
10190 NN=NN+1:PRINT "~C4";CHR$(28);CHR$(21);NN
10200 GOTO 10170
10201 'END OF PROGRAM DATAPROC
10202 '=========================
```

APPENDIX C. HIGH-RESOLUTION PLOTTING SUBPROGRAMS

Disassembled from memory address 42D0H to 444DH

(Numbers are printed in hexadecimal notation, upper byte first separated from lower byte by :)

```
42D0 --- EXX
42D1 --- LD    HL,B4:E8
42D4 --- LD    BC,E:16
42D7 --- LD    E,32
42D9 --- IN    A,(4D)
42DB --- BIT   1,A
42DD --- JP    NZ,42:EA
42E0 --- DEC   E
42E1 --- LD    A,0
42E3 --- CP    E
42E4 --- JP    NZ,42:D9
42E7 --- JP    43:17
42EA --- IN    A,(4C)
42EC --- BIT   7,A
42EE --- JP    NZ,43:10
42F1 --- DEC   BC
42F2 --- JP    42:D7
42F5 --- LD    E,32
42F7 --- IN    A,(4D)
42F9 --- BIT   1,A
42FB --- JP    Z,43:10
42FE --- IN    A,(4C)
4300 --- LD    (HL),A
4301 --- INC   HL
4302 --- DEC   BC
4303 --- LD    A,0
4305 --- CP    B
4306 --- JP    NZ,42:F5
4309 --- CP    C
430A --- JP    NZ,42:F5
430D --- JP    43:1B
4310 --- DEC   E
4311 --- LD    A,0
4313 --- CP    E
4314 --- JP    NZ,42:F7
4317 --- LD    (42:CC),A
431A --- RET
431B --- LD    HL,B5:30
431E --- LD    DE,BF:CE
4321 --- LD    BC,01:49
4324 --- LDD
4326 --- LD    A,0
4328 --- CP    C
4329 --- JP    NZ,43:24
432C --- LD    IY,B4:E8
4330 --- LD    E,3
4332 --- LD    IX,A7:F8
4336 --- LD    (IX+0),1
433A --- INC   IX
```

```
433C --- LD    (IX+0),47
4340 --- INC   IX
4342 --- LD    (IX+0),1
4346 --- INC   IX
4348 --- LD    (IX+0),42
434C --- INC   IX
434E --- JP    43:F8
4351 --- LD    HL,01:3F
4354 --- LD    BC,1:BE
4357 --- INC   HL
4358 --- LD    D,H
4359 --- SLA   D
435B --- SLA   D
435D --- LD    A,L
435E --- SRL   A
4360 --- SRL   A
4362 --- SRL   A
4364 --- SRL   A
4366 --- SRL   A
4368 --- SRL   A
436A --- ADD   A,D
436B --- AND   7
436D --- ADD   A,40
436F --- INC   IX
4371 --- LD    (IX+0),A
4374 --- DEC   IX
4376 --- LD    A,L
4377 --- AND   3F
4379 --- ADD   A,40
437B --- LD    (IX+0),A
437E --- INC   IX
4380 --- INC   IX
4382 --- LD    A,(IY+0)
4385 --- SLA   A
4387 --- SLA   A
4389 --- SLA   A
438B --- SLA   A
438D --- LD    D,A
438E --- INC   IY
4390 --- LD    A,(IY+0)
4393 --- SRL   A
4395 --- SRL   A
4397 --- SRL   A
4399 --- ADD   A,D
439A --- SRL   A
439C --- CP    64
439E --- JP    M,43:A6
43A1 --- LD    A,C7
43A3 --- JP    43:A8
```

```
43A6 --- SLA    A              43F5 --- LD     (HL),1
43A8 --- INC    IY             43F7 --- RET
43AA --- ADD    A,37           43F8 --- INC    IY
43AC --- LD     D,A            43FA --- INC    IY
43AD --- AND    3F             43FC --- INC    IY
43AF --- ADD    A,40           43FE --- INC    IY
43B1 --- LD     (IX+0),A       4400 --- LD     (IX+0),28
43B4 --- INC    IX             4404 --- INC    IX
43B6 --- LD     A,D            4406 --- LD     (IX+0),1
43B7 --- AND    C0             440A --- INC    IX
43B9 --- SRL    A              440C --- LD     (IX+0),43
43BB --- SRL    A              4410 --- INC    IX
43BD --- SRL    A              4412 --- LD     A,(IY+0)
43BF --- SRL    A              4415 --- AND    30
43C1 --- SRL    A              4417 --- SRL    A
43C3 --- SRL    A              4419 --- SRL    A
43C5 --- ADD    A,40           441B --- SRL    A
43C7 --- LD     (IX+0),A       441D --- SRL    A
43CA --- INC    IX             441F --- CP     0
43CC --- DEC    BC             4421 --- JP     Z,442E
43CD --- LD     A,0            4424 --- CP     1
43CF --- CP     B              4426 --- JP     Z,4433
43D0 --- JP     NZ,4357        4429 --- LD     A,31
43D3 --- CP     C              442B --- JP     4435
43D4 --- JP     NZ,4357        442E --- LD     A,34
43D7 --- DEC    E              4430 --- JP     4435
43D8 --- CP     E              4433 --- LD     A,32
43D9 --- JP     NZ,434E        4435 --- LD     (IX+0),A
43DC --- LD     (IX+0),1       4438 --- INC    IX
43E0 --- INC    IX             443A --- LD     (IX+0),1
43E2 --- LD     (IX+0),3A      443E --- INC    IX
43E6 --- INC    IX             4440 --- LD     (IX+0),3A
43E8 --- LD     (IX+0),46      4444 --- INC    IX
43EC --- INC    IX             4446 --- LD     (IX+0),A
43EE --- LD     (IX+0),1E      4449 --- INC    IX
43F2 --- INC    IX             444B --- JP     4351
43F4 --- EXX
```

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APPENDIX D. HIGH-SPEED PLOTTING SUBPROGRAMS

Disassembled from memory address 445CH to 45F0H

(Numbers are printed in hexadecimal notation, upper byte first separated from lower byte by :)

```
445C --- EXX                          44C3 --- LD     IX+0),42
445D --- LD    HL,B4:E8               44C7 --- INC    IX
4460 --- LD    BC,E:1                 44C9 --- JP     45:82
4463 --- LD    E,32                   44CC --- LD     HL,0:3F
4465 --- IN    A,(4D)                 44CF --- LD     BC,0:6F
4467 --- BIT   1,A                    44D2 --- INC    HL
4469 --- JP    NZ,44:76               44D3 --- INC    HL
446C --- DEC   E                      44D4 --- INC    HL
446D --- LD    A,0                    44D5 --- INC    HL
446F --- CP    E                      44D6 --- LD     D,H
4470 --- JP    NZ,44:65               44D7 --- SLA    D
4473 --- JP    44:A3                  44D9 --- SLA    D
4476 --- IN    A,(4C)                 44DB --- LD     A,L
4478 --- BIT   7,A                    44DC --- SRL    A
447A --- JP    NZ,44:8C               44DE --- SRL    A
447D --- DEC   BC                     44E0 --- SRL    A
447E --- JP    44:63                  44E2 --- SRL    A
4481 --- LD    E,32                   44E4 --- SRL    A
4483 --- IN    A,(4D)                 44E6 --- SRL    A
4485 --- BIT   1,A                    44E8 --- ADD    A,D
4487 --- JP    Z,44:9C                44E9 --- AND    7
448A --- IN    A,(4C)                 44EB --- ADD    A,40
448C --- LD    (HL),A                 44ED --- INC    IX
448D --- INC   HL                     44EF --- LD     (IX+0),A
448E --- DEC   BC                     44F2 --- DEC    IX
448F --- LD    A,0                    44F4 --- LD     A,L
4491 --- CP    B                      44F5 --- AND    3F
4492 --- JP    NZ,44:81               44F7 --- ADD    A,40
4495 --- CP    C                      44F9 --- LD     (IX+0),A
4496 --- JP    NZ,44:81               44FC --- INC    IX
4499 --- JP    44:A7                  44FE --- INC    IX
449C --- DEC   E                      4500 --- LD     A,(IY+C)
449D --- LD    A,0                    4503 --- SLA    A
449F --- CP    E                      4505 --- SLA    A
44A0 --- JP    NZ,44:83               4507 --- SLA    A
44A3 --- LD    (42:CC),A              4509 --- SLA    A
44A6 --- RET                          450B --- LD     D,A
44A7 --- LD    IY,B4:E8               450C --- INC    IY
44A9 --- LD    E,3                    450E --- LD     A,(IY+0)
44AD --- LD    IX,A7:F8               4511 --- SRL    A
44B1 --- LD    (IX+0),1               4513 --- SRL    A
44B5 --- INC   IX                     4515 --- SRL    A
44B7 --- LD    (IX-0),47              4517 --- ADD    A,D
44BB --- INC   IX                     4518 --- SRL    A
44BD --- LD    (IX+0),1               451A --- CP     64
44C1 --- INC   IX                     451C --- JP     N,45:24
```

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```
451F --- LD     A,C7
4521 --- JP     45!26
4524 --- SLA    A
4526 --- INC    IY
4528 --- INC    IY
452A --- INC    IY
452C --- INC    IY
452E --- INC    IY
4530 --- INC    IY
4532 --- INC    IY
4534 --- ADD    A,37
4536 --- LD     D,A
4537 --- AND    3F
4539 --- ADD    A,40
453B --- LD     (IX+0),A
453E --- INC    IX
4540 --- LD     A,D
4541 --- AND    C0
4543 --- SRL    A
4545 --- SRL    A
4547 --- SRL    A
4549 --- SRL    A
454B --- SRL    A
454D --- SRL    A
454F --- ADD    A,40
4551 --- LD     (IX+0),A
4554 --- INC    IX
4556 --- DEC    BC
4557 --- LD     A,0
4559 --- CP     B
455A --- JP     NZ,44!D2
455D --- CP     C
455E --- JP     NZ,44!D2
4561 --- DEC    E
4562 --- CP     E
4563 --- JP     NZ,44!C9
4566 --- LD     (IX+0),1
456A --- INC    IX
456C --- LD     (IX+0),3A
4570 --- INC    IX
4572 --- LD     (IX+0),46
4576 --- INC    IX
4578 --- LD     (IX+0),1E
457C --- INC    IX
457E --- EXX
457F --- LD     (HL),1

4581 --- RET
4582 --- INC    IY
4584 --- INC    IY
4586 --- INC    IY
4588 --- INC    IY
458A --- INC    IY
458C --- INC    IY
458E --- INC    IY
4590 --- INC    IY
4592 --- LD     (IX+0),28
4596 --- INC    IX
4598 --- LD     (IX+0),1
459C --- INC    IX
459E --- LD     (IX+0),43
45A2 --- INC    IX
45A4 --- LD     A,(IY+0)
45A7 --- AND    30
45A9 --- SRL    A
45AB --- SRL    A
45AD --- SRL    A
45AF --- SRL    A
45B1 --- CP     0
45B3 --- JP     Z,45!C0
45B6 --- CP     1
45B8 --- JP     Z,45!C5
45BB --- LD     A,31
45BD --- JP     45!C7
45C0 --- LD     A,34
45C2 --- JP     45!C7
45C5 --- LD     A,32
45C7 --- LD     (IX+0),A
45CA --- INC    IX
45CC --- LD     (IX+0),1
45D0 --- INC    IX
45D2 --- LD     (IX+0),3A
45D6 --- INC    IX
45D8 --- LD     (IX+0),A
45DB --- INC    IX
45DD --- JP     44!CC
```

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